# A detailed study of carbon chemical erosion in L-mode plasmas in the DIII-D divertor


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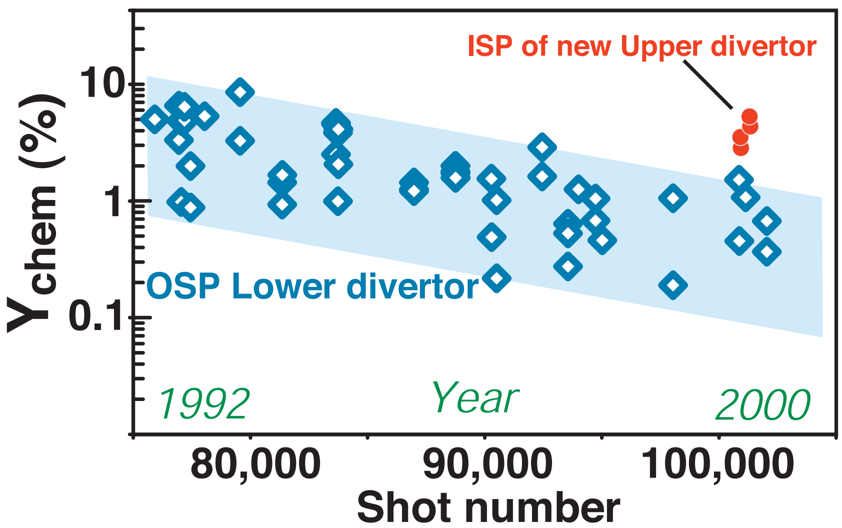
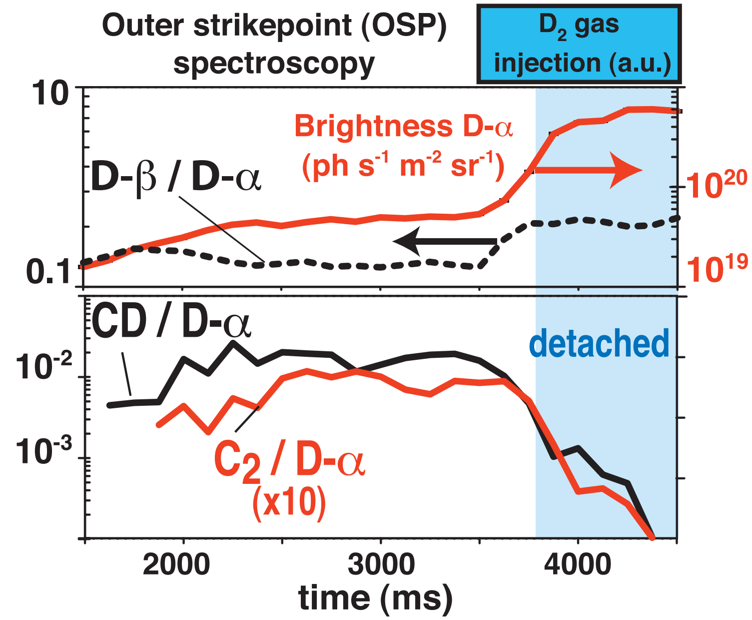
# Outline

- L-mode plasmas for carbon erosion studies
- Erosion modeling and interpretation
- Erosion with attached divertor plasma
  - Divertor tile vs. main-wall tile
  - Determination of $Y_{chem}$ at outer strikepoint
  - Atomic carbon velocity distribution
- Effect of plasma detachment on carbon erosion.
- Discussion & Summary

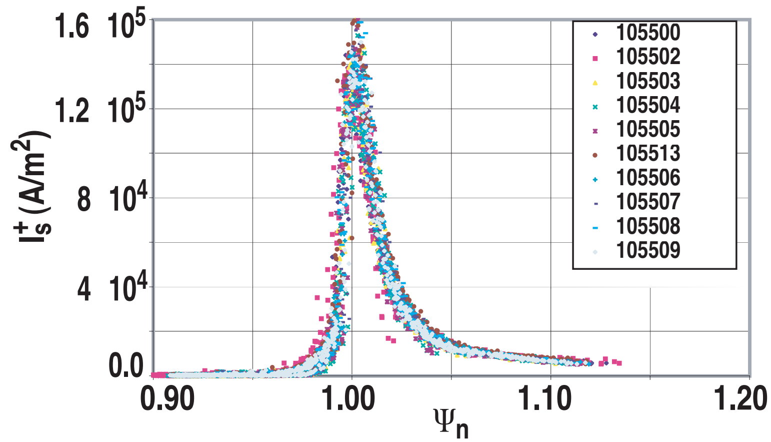
# H-mode plasma studies showed unexpected reduction in carbon erosion in the DIII-D divertor

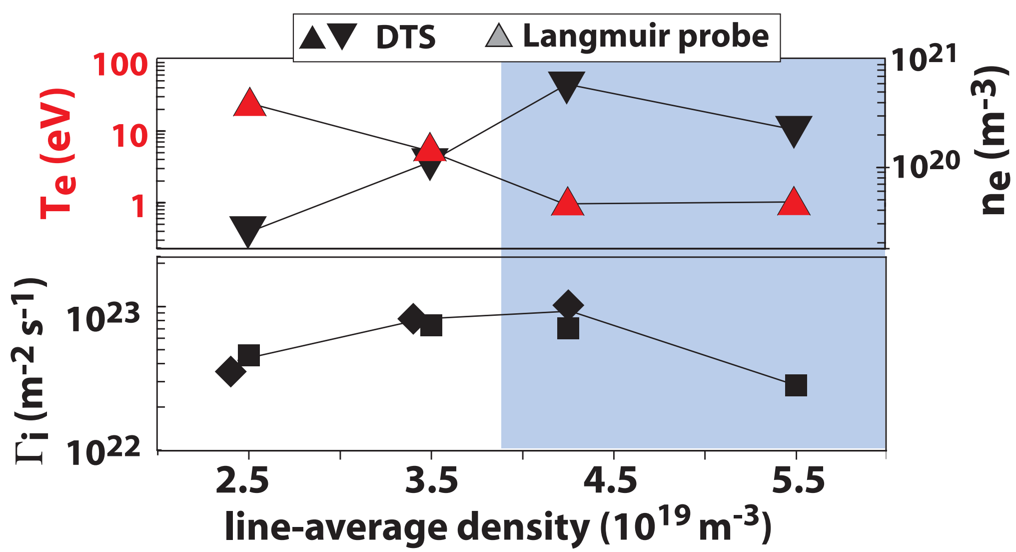



- Encouraging results on the use of carbon:
  - In-situ $Y_{chem}$ reduction at lower divertor.
  - Detachment, necessary for heat flux control, greatly reduces HC signals
- …but *tentative* results:
  - Inconsistent plasma conditions over long-term study
  - ELMs in H-mode complicate interpretation of erosion and spectroscopy.

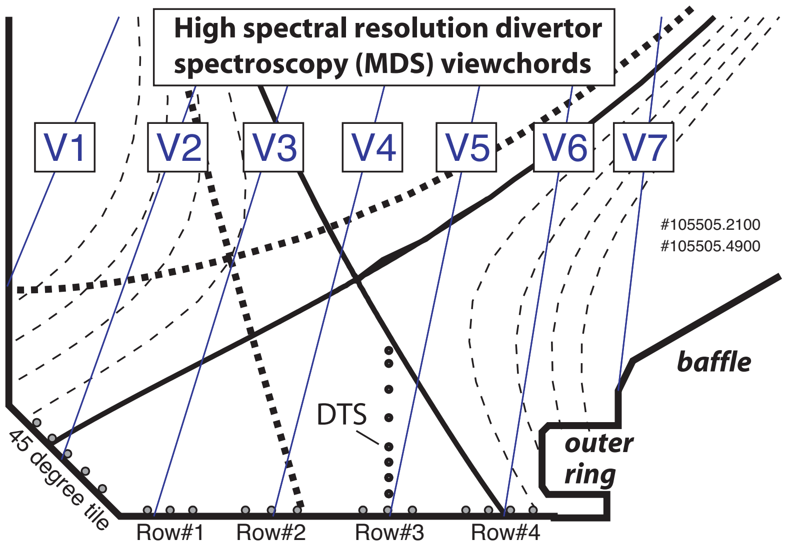
# L-mode, simple-as-possible plasmas ideal for carbon studies



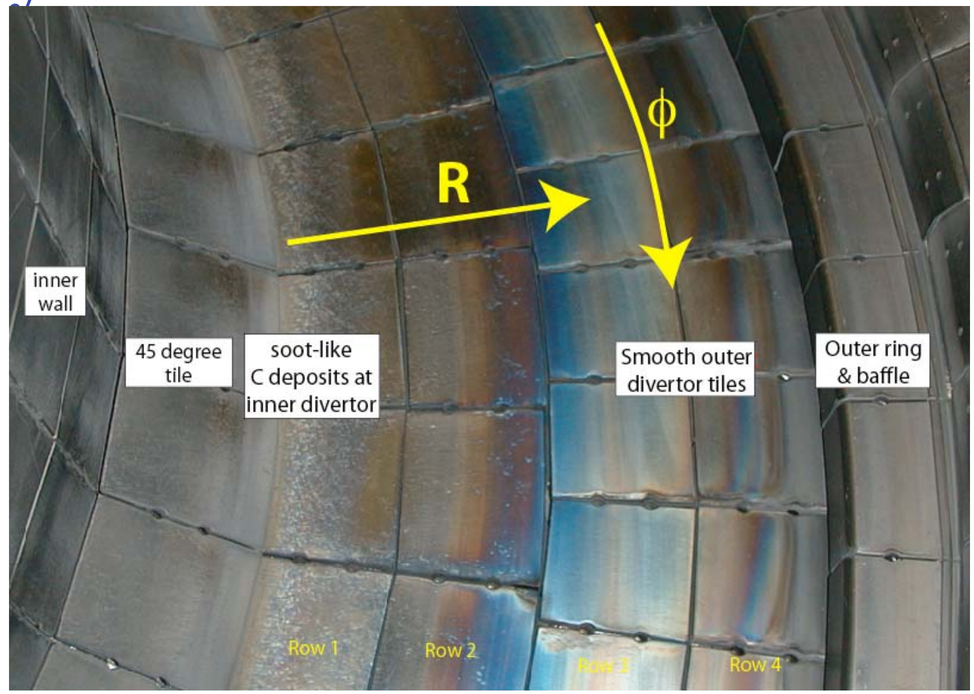




- Low power leads to ~ constant $T_{surf}$~375 K
- No ELMs
- Density control leads to good detachment control
- Multiple discharges
  - Improved DTS statistics
  - Redundant divertor diagnosis
  - Multiple C & HC emissions measured.

# High resolution spectroscopy and divertor sweeping diagnose erosion over wide variety of surfaces




Langmuir probe clusters on lower divertor tiles




- Absolute wavelength calibration from discharge lamps during plasma shot (+/- 0.001 nm ~ 300 m/s).
- Can resolve $T_C < 0.5$ eV.

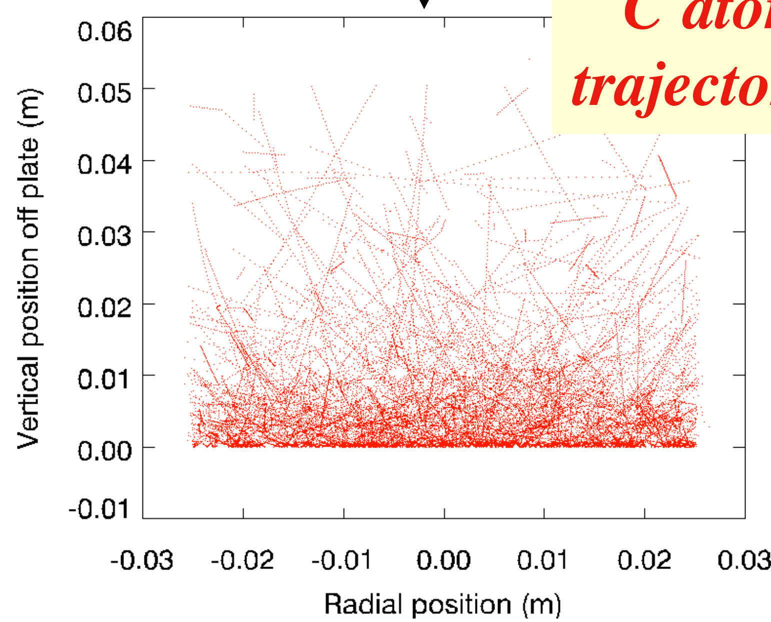
- Divertor tiles made from ATJ graphite, an isostatically molded fine grain graphite
- Multiple (>50) boronization layers applied over +10 year lifetime.

# WBC Monte-Carlo code is used to interpret HC spectroscopy

- Full dissociation chains of methane & higher order HC's
- MOLDYN reflections vs. E
- Full HC spectrum launched into OSP plasma (DTS) with sonic flow to plate.
- Particle followed until redeposition or leave simulation zone (~5-10 cm)
- Added $C_2$ and $C_3$ rates for $C_2$ spectroscopic interpretation.
  - ➢ Close to C for ionization & diss. CX negligible in H plasma
- Excitation rates of CD, $C_2$, C I and CII vs. $T_{e,}n_e$ to calculate expected emission --> photon efficiency.

**43.5% $CD_4$, 3.7% $C_2D_2$, 24.8% $C_2D_4$, 11% $C_2D_6$, 16% $C_3D_6$**

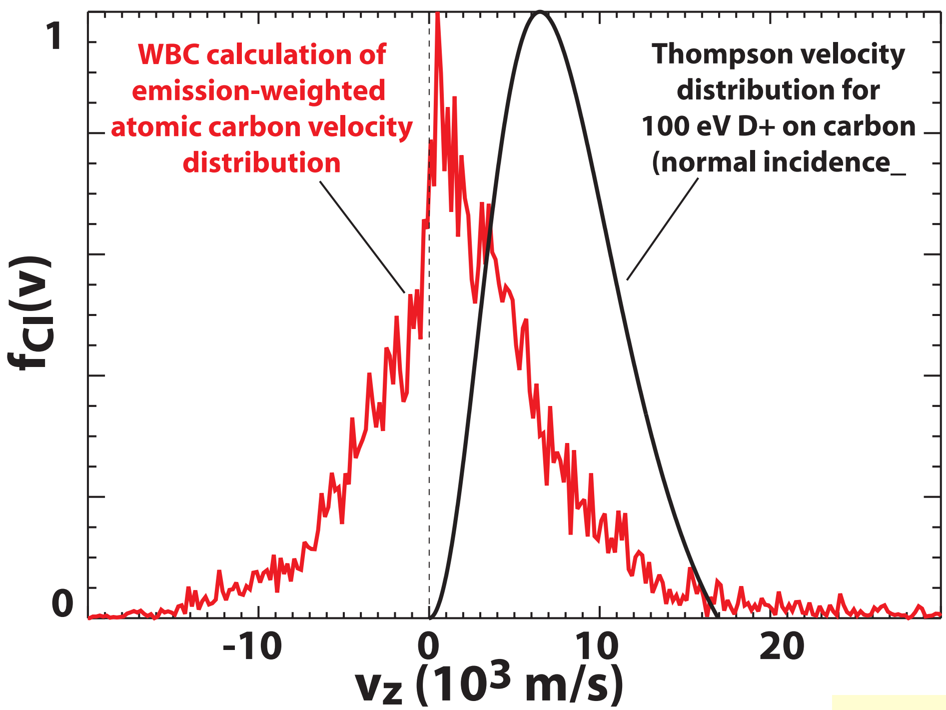
*C atom trajectories*




**CI photon efficiency**

$$\left(\frac{XB}{S}\right)_{CI,910nm} = \sum_i n_e\ X_{CI,910nm}(T_e)\ \Delta t_{i,CI}$$

# Atomic carbon velocity distribution can be an indicator of erosion source

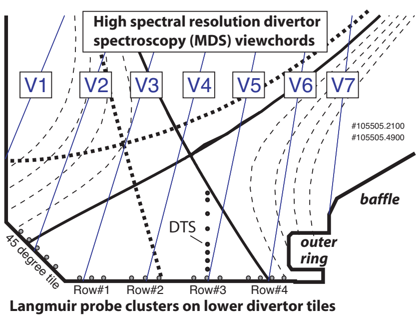


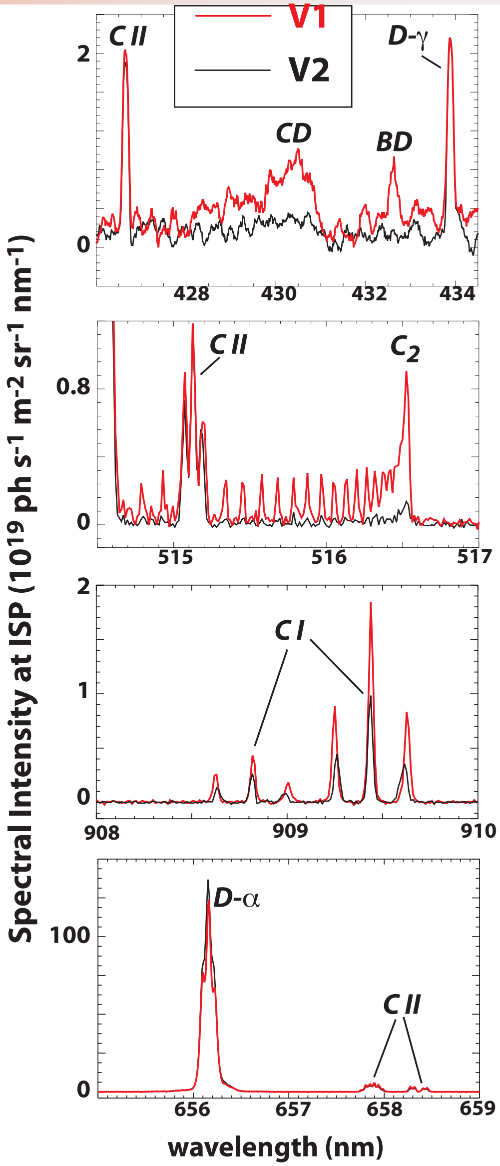

- WBC computes emission weighted $f(v_z)$ arising from HC dissociation into C I.
- Thompson model with light-ion energy cutoff/correction predicts direct CI $f(v_z)$ from D+ on C physical sputtering.

$$\frac{df_v(E)}{dv} \propto \left(\frac{E^{3/2}}{(E+E_B)^3}\right)\left(1-\left(\frac{E_B+E}{\gamma(1-\gamma)E}\right)^{1/2}\right)$$

$$\gamma = \frac{4\mathrm{m_C} m_D}{(\mathrm{m_C}+m_D)^2} \sim 0.49$$

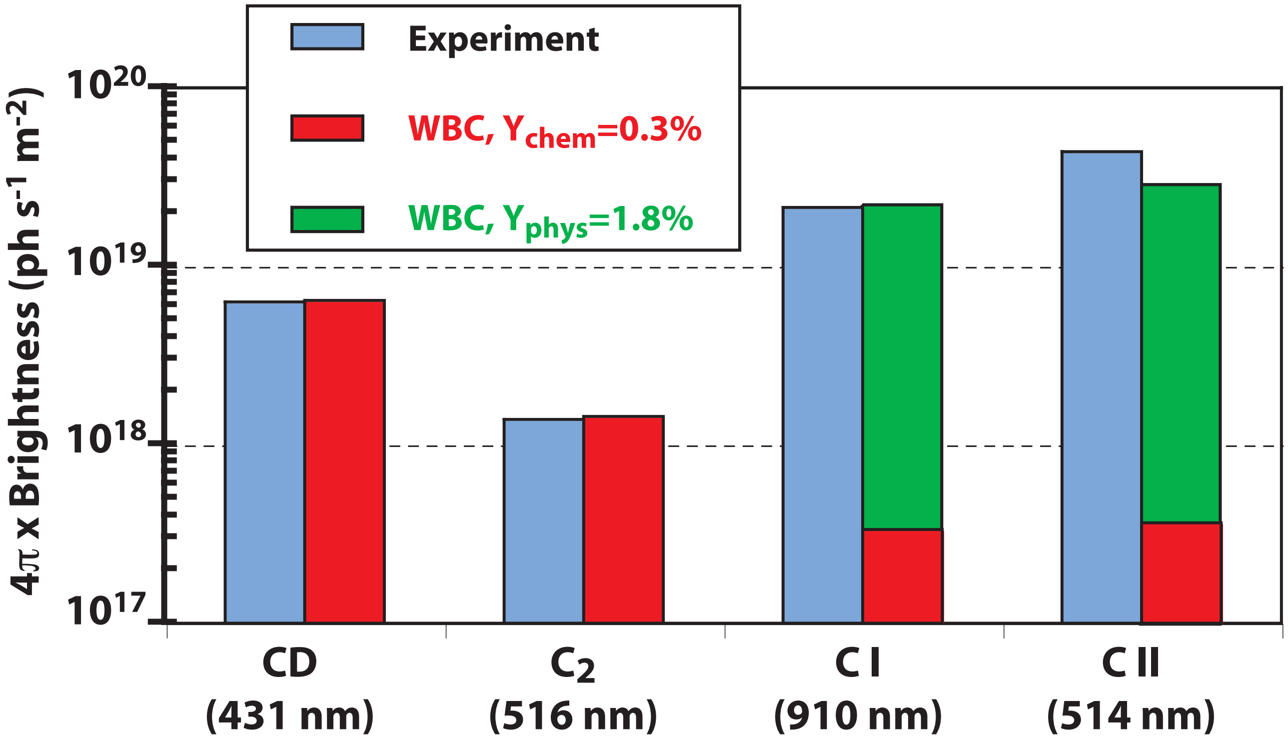
# The main/inner wall tiles has 5-6 times higher $Y_{chem}$ than the inner divertor tiles



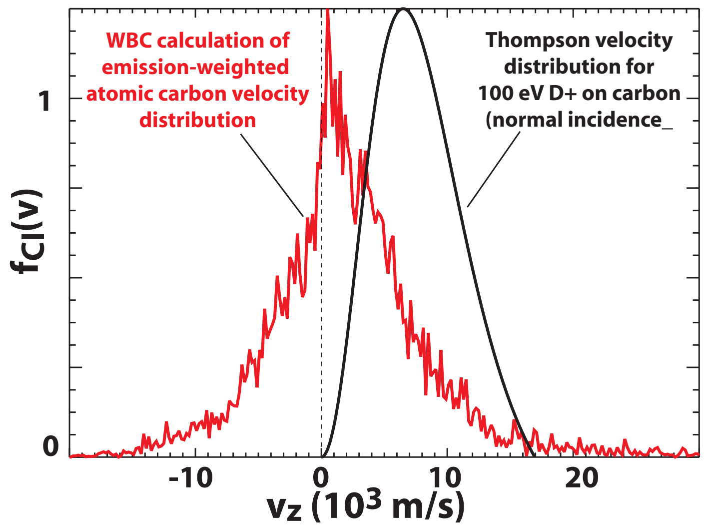

- V1 is a rare location for ISP, small particle/energy fluence.
- Spectroscopy verifies ~identical ISP plasmas at two locations:
  $T_e \sim 10$ eV
  $n_e \sim 1.5 \times 10^{19}$ m$^{-3}$
- Boron (BD) higher from inner wall.

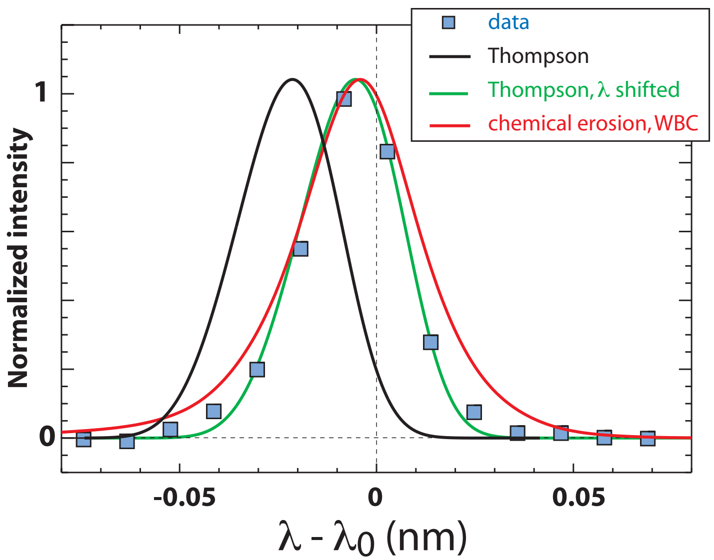
# Attached outer strikepoint is dominated by physical sputtering , $Y_{chem}$= 0.3%




- Incident plasma: $T_e$=20 eV, $E_i$~5 T=100 eV, $n_e$ ~2.5x$10^{19}$ $m^{-3}$
- Matches of CD/$C_2$ ratio gives confidence in HC modeling.
- Match of CII/CI ratio gives confidence in ion transport modeling.

# Neither erosion model fits the CI spectral features.




- Calculated $f(v_z)$ convoluted with spectrometer instrumental function for comparison to measured CI spectra.

- Discrepancy with sputtering models unresolved.
  - Physical: $T_{eff}$ ~ 1 eV OK, shift too large
  - Chemical - WBC: shift OK, but $T_{eff}$~3 eV too large.

- *N.B. chemical erosion can actually lead to higher $T_{eff,CI}$ than physical sputtering*

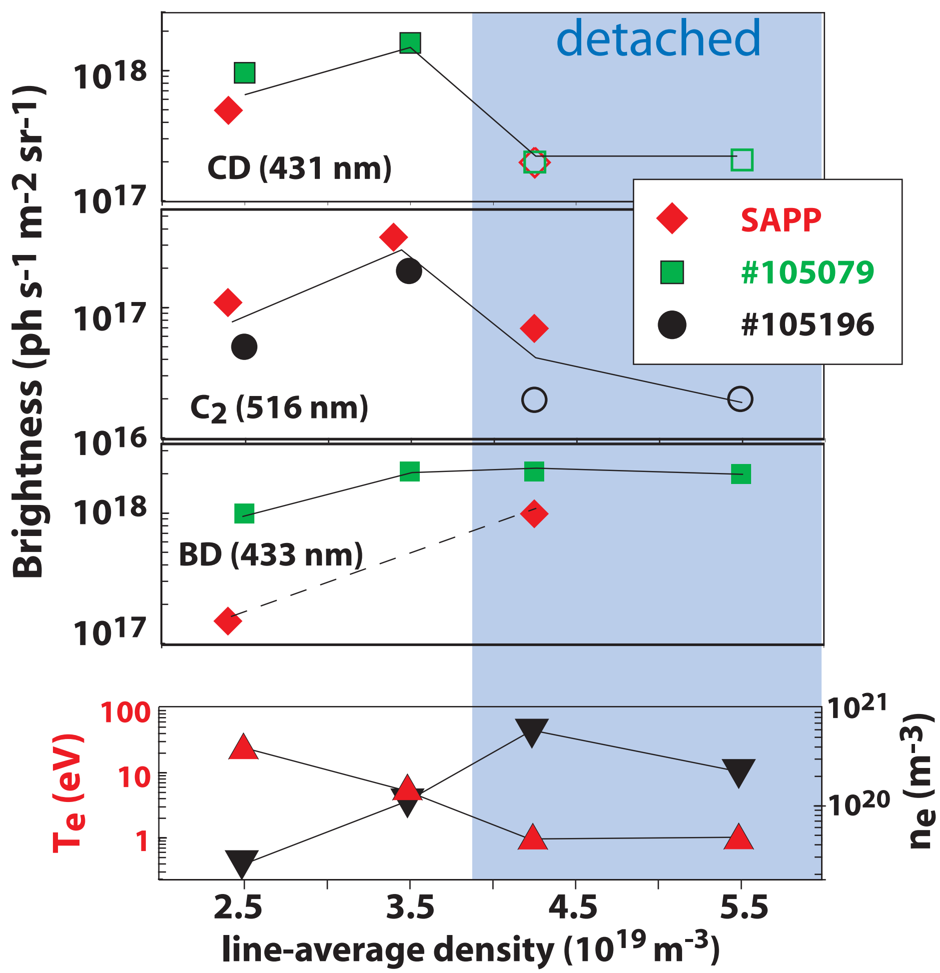
# WBC modeling predicts increasing photon efficiency in detached plasmas

| CASE | ***WBC-20*** | ***WBC-21*** | ***WBC-22*** |
| --- | --- | --- | --- |
| **Plasma parameters at outer strikepoint** | | | |
| *Te (eV)* | 20 | 5 | 1 |
| $n_e$ *(*$m^{-3}$*)* | 2.5e19 | 1.05e20 | 5.6e20 |
| **Photon-emission excitation rate coefficients (**$m^3$ **/ s)** | | | |
| *C I (910 nm)* | 1.7e-15 | 1.5e-17 | 5.e-19 |
| *CD (431 nm)* | 5.6e-15 | 7e-15 | 1.5e-15 |
| $C_2$ *(516 nm)* | 2e-14 | 4e-14 | 1.16e-14 |
| $C^+$ *(514 nm)* | 5e-16 | nil | nil |
| **Photon efficiencies: Full hydrocarbon spectrum launched** | | | |
| *C I* | 4.4e-03 | 1.6e-3 | 1.7e-3 |
| *CD* | 5.1e-2 | 0.45 | 0.22 |
| $C_2$ | **1.1e-2** | **0.83** | **9.8** |
| *C II* | 4.2e-3 | --- | --- |

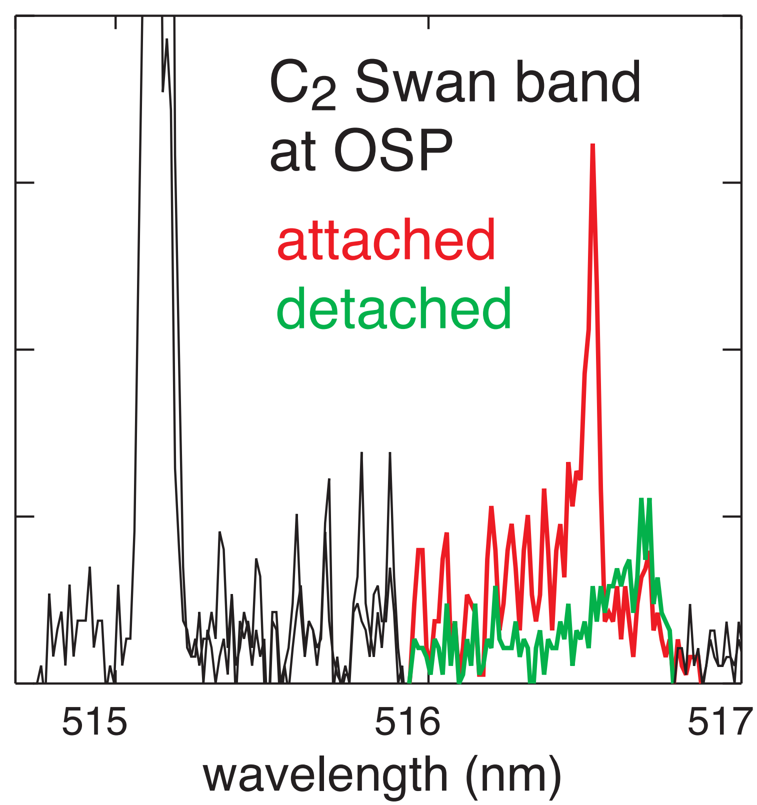
- $C_2$ is particularly interesting case:
in 1 eV plasma no e- impact ionization /dissociation but readily excited by e- impact ($E_{th}$~2.4 eV).

- In qualitative agreement with $C_2D_4$ injection on JET at high density…$C_2$ most easily excited (Stamp et al.)

# Detachment strongly suppresses signatures of chemical erosion at the OSP




- HC brightness decreases to or below detection limits (open symbols) in detachment.



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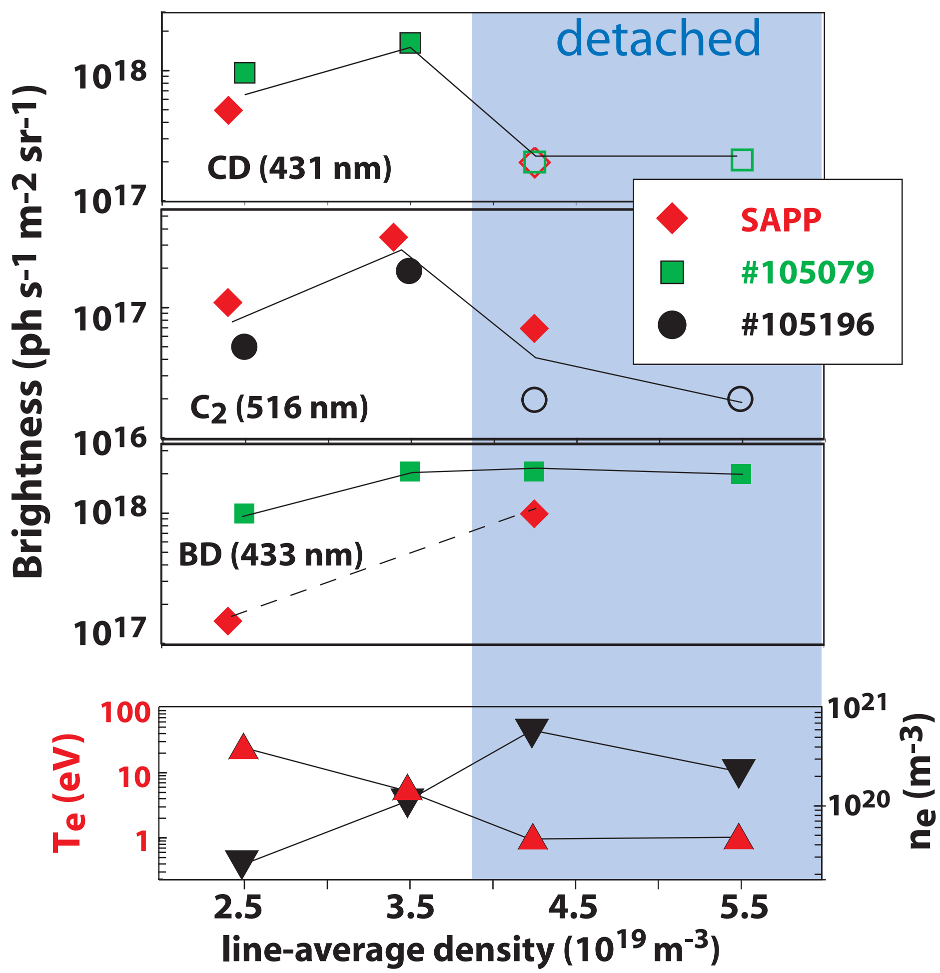
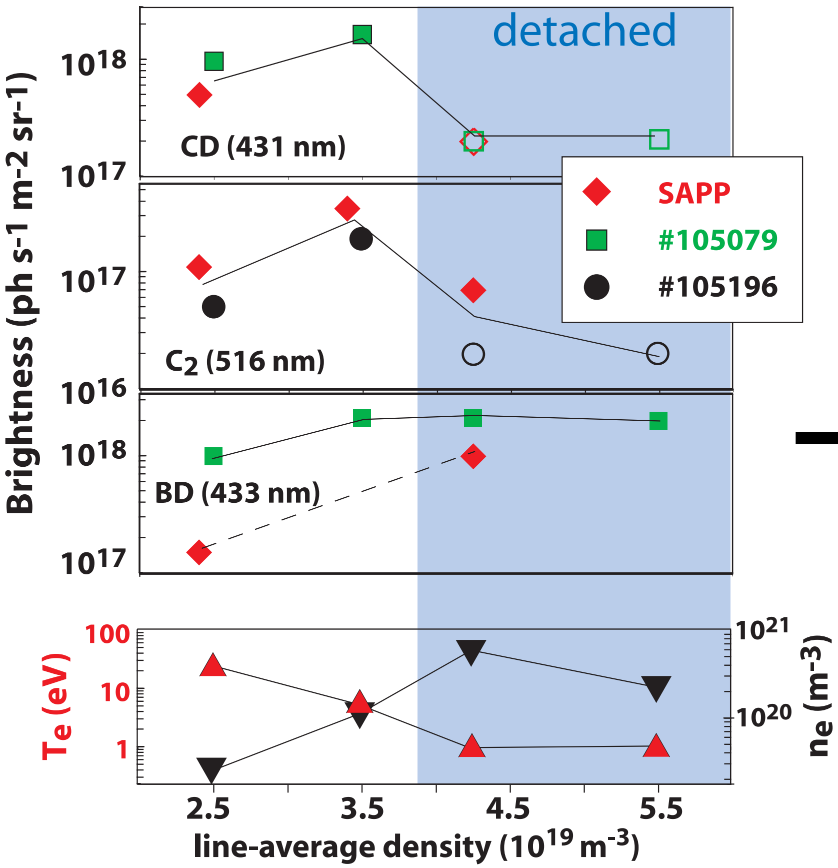
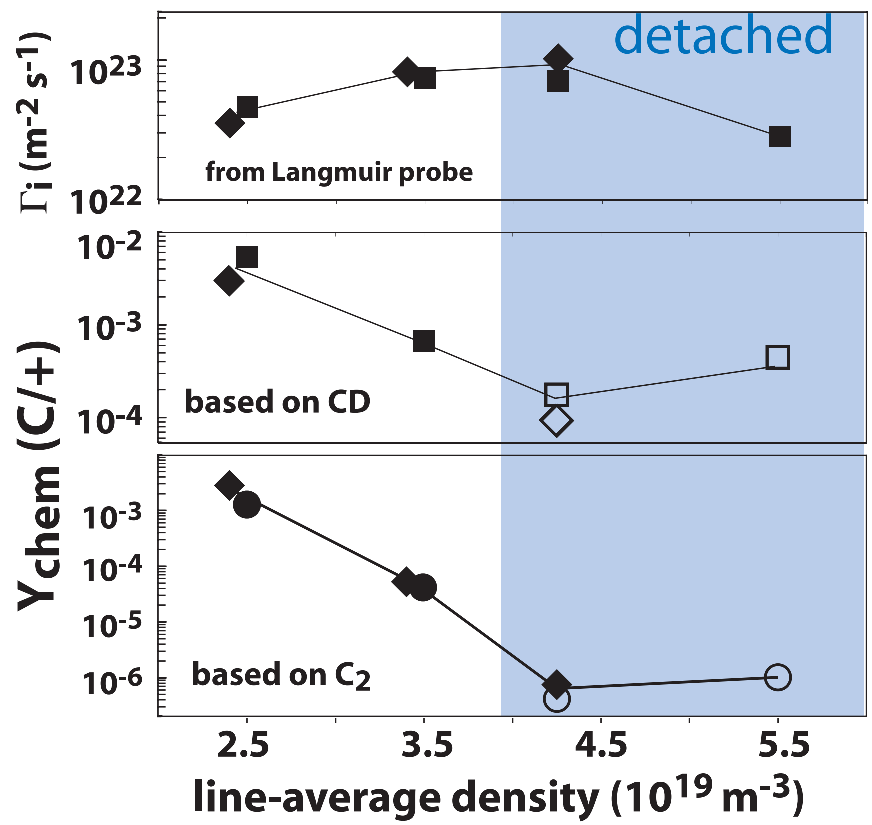



- HC brightness decreases to or below detection limits (open symbols) in detachment.

- BD behavior significant:
  - ➢ Must radiate in detached plasma (MFP ~1 mm)
  - ➢ Verifies $T_e$ ~ 1 eV to sustain BD emission.
  - ➢ Ultra-low $T_e$ cannot be cause of extinction of HC emission, since $E_{th}$ ~ identical between BD & CD.

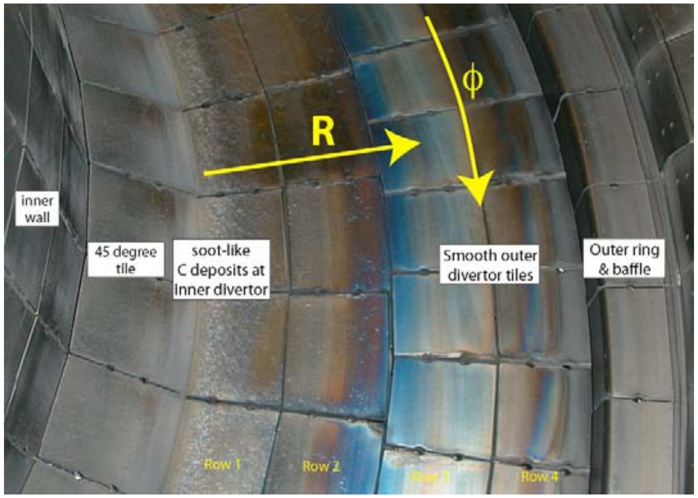
# Detachment strongly suppresses signatures of chemical erosion at the OSP: $Y_{chem} \leq 10^{-4}$

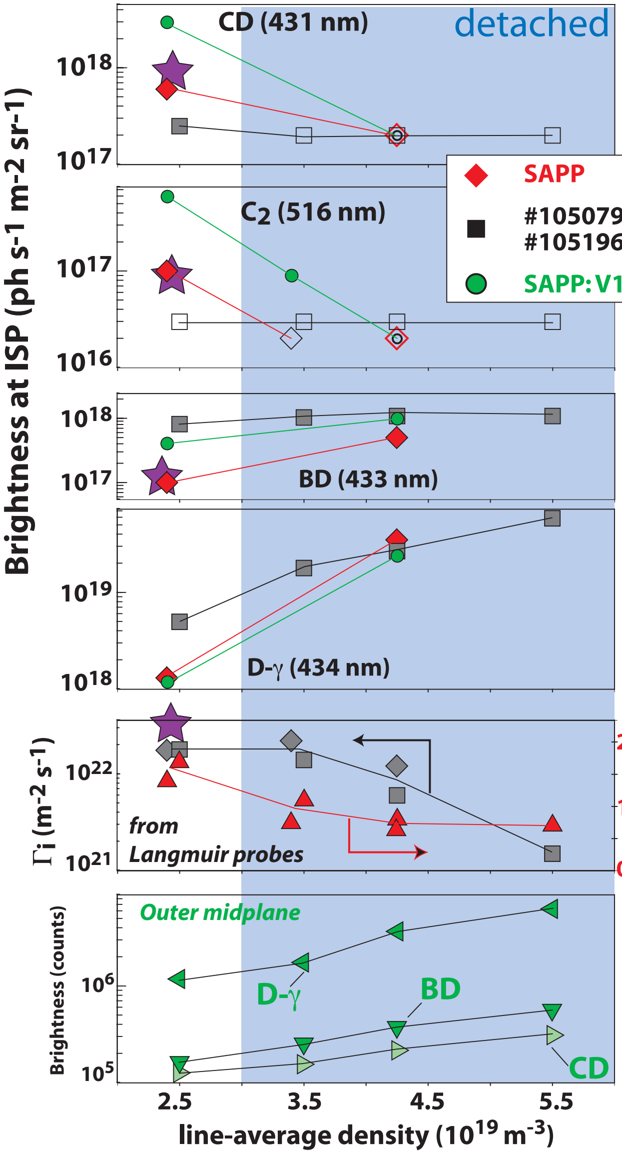


# ISP behaves nearly identical to OSP:
## No apparent difference between locations in $Y_{chem}$

- Implies $Y_{chem}$ ~0.3% in attached case.
  - ➢ No DTS for modeling.
- No difference between net erosion dominated OSP (stars) and sooty, redeposited ISP tiles.




**ISP vs. ⟨$n_e$⟩**

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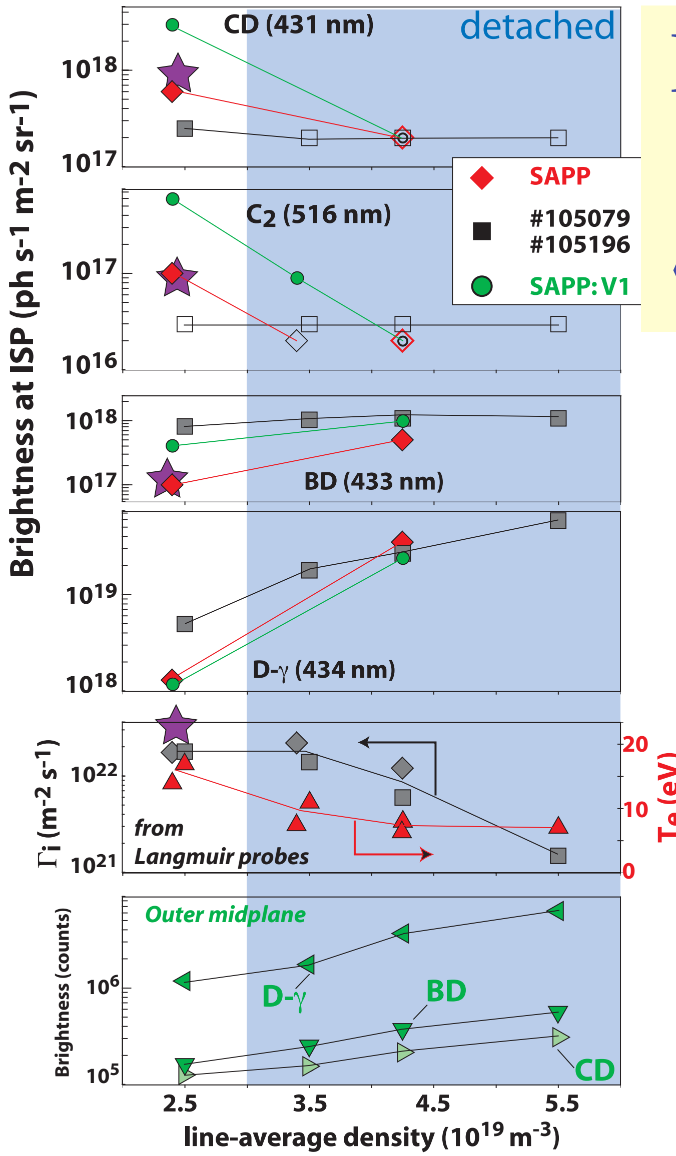
### FURTHER OBSERVATIONS

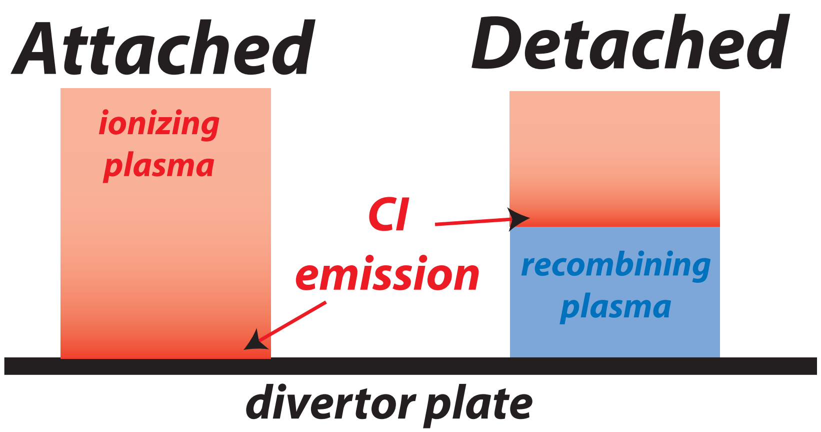
- BD presence: $T_e$ can support HC emission.
- Lack of HC emission --> little chemical erosion in detached ISP.
- In stark contrast to the divertor, main-wall chemical erosion increases with ~ constant yield.

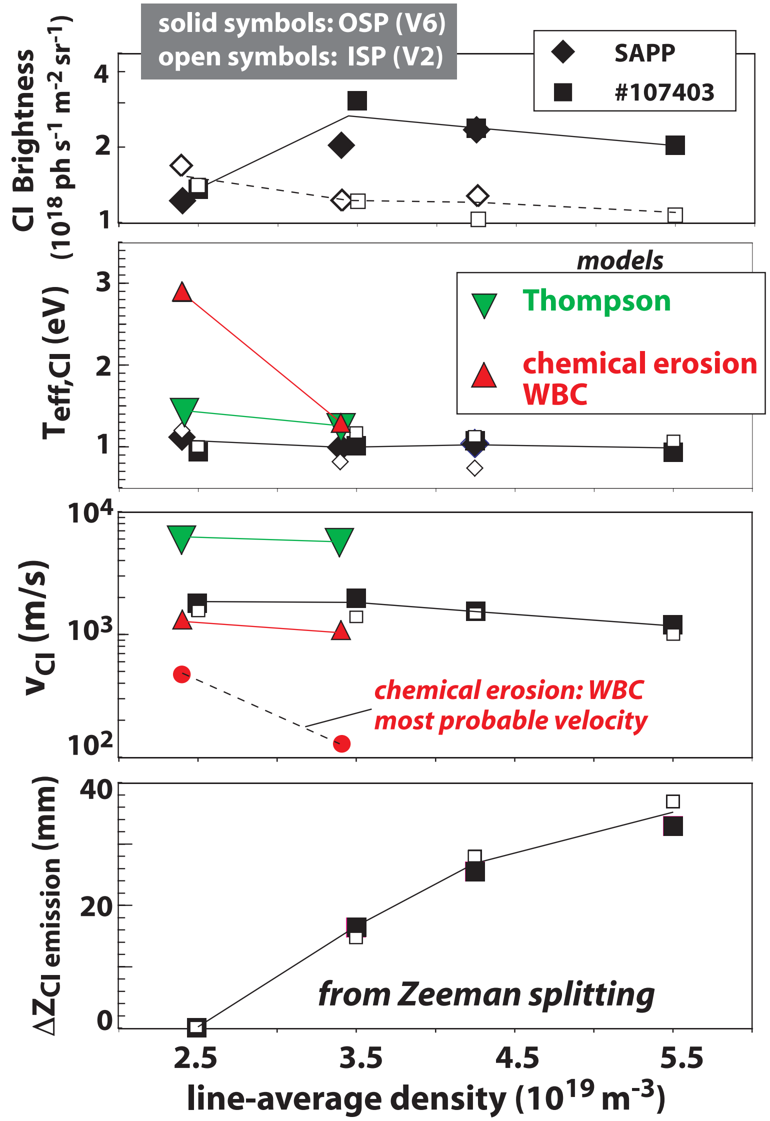



ISP vs. ⟨$n_e$⟩

# Divertor atomic carbon response to detachment varies greatly from HC

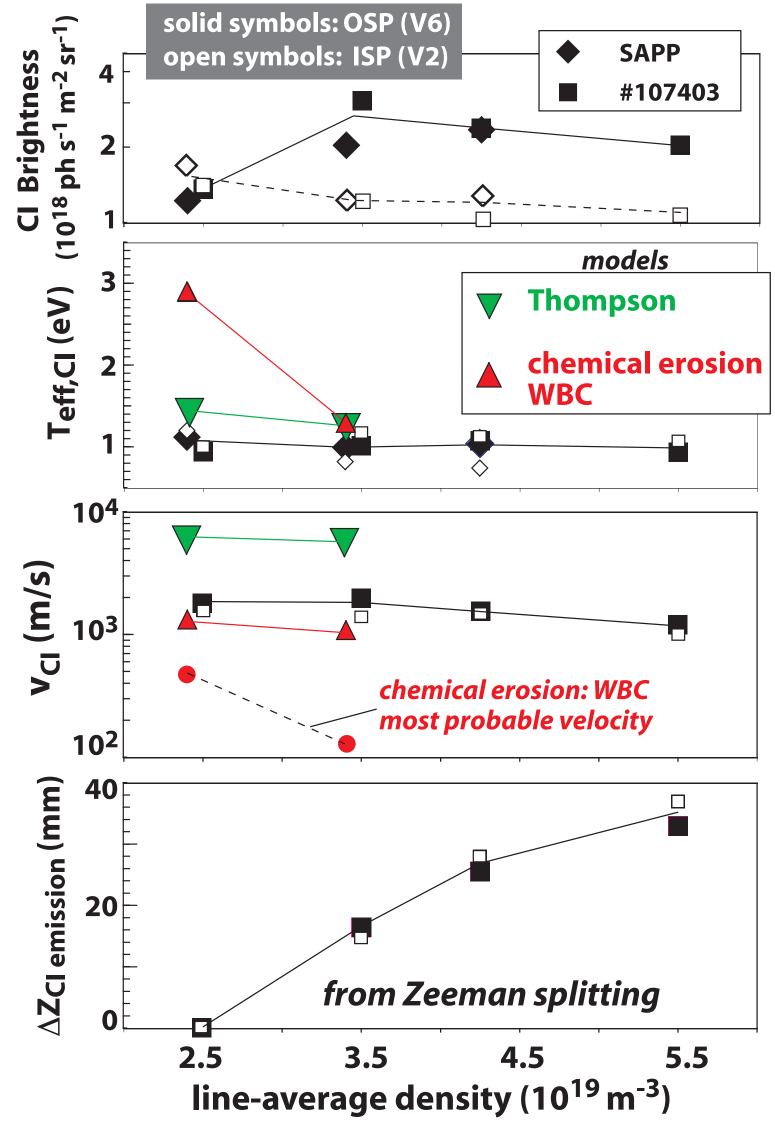
- CI brightness is ~ proportional to ion flux.
- Change in Zeeman splitting indicates CI emitted from ionization front.



# Divertor atomic carbon response to detachment varies greatly from HC

- CI brightness is ~ proportional to ion flux.
- Change in Zeeman splitting indicates CI emitted from ionization front.
- Little or no change in $T_{eff}$, contradictory to chemical erosion.
- Doppler shift remains inconsistent with physical sputtering.



# Discussion on dependence of location for $Y_{chem}$

- Redeposited layers, e.g inner divertor do **not** have higher chemical erosion.
  - No difference between ISP & OSP, regions yet  dominated by net erosion &deposition respectively.
  - At strikepoints, almost all C atoms/HC eroded are from a deposited film, since prompt redepositon on ~90%.
- Results indicate **against** importance of boron in reduction.
  - Slighter higher $Y_{chem}$ after boronization
  - Upper inner wall and main-wall, strong boron presence with no apparent reduction
- Large energy / particle fluence in divertor remains as the “cause” in the relative reduction.

# Discussion on the (near) extinction of HC emission in detachment.

- Accuracy of yield < $10^{-4}$ unknown, but the general results of WBC follow from simple examination
  - The HC dissociation chain is simplified by the lack of ionizing event, → the HC should produce $C_2$ &/or CD
  - BD shows $C_2$ and CD should radiate efficiently.

- The absence of $C_2$ &/or CD argues strongly **against**:

**1.** The importance of chemical erosion as a carbon source for the plasma (*does not produce C ions*) and

**2.** A large role for chemical erosion in determining net erosion / deposition (*MFP of HC molecules < mm << MFP CI, CII*).

# In summary we have verified and further quantified previous H-mode results of carbon erosion, with some new obervations

- Chemical erosion is weak in the DIII-D lower divertor, $Y_{chem}$ ~0.3 % with attached plasma.

- Same shot comparison indicates that the divertor tiles have less chemical erosion than main, inner wall.
  - Boron does not appear to be cause of reduction.

- Detachment eliminates the spectroscopic signature of chemical erosion, with a inferred yield through modeling < $10^{-4}$.